LA-UR-20-24787
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Title: Varying Quantum Degeneracy in Plasmas Created at the National Ignition Facility

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Intended for: Seminar in T-2, LANL on July 7th 2020

Issued: 2020-07-01

Varying Quantum Degeneracy in Plasmas Created at the National Ignition Facility

Nature Physics, Vol 16, 2020, p 432-437

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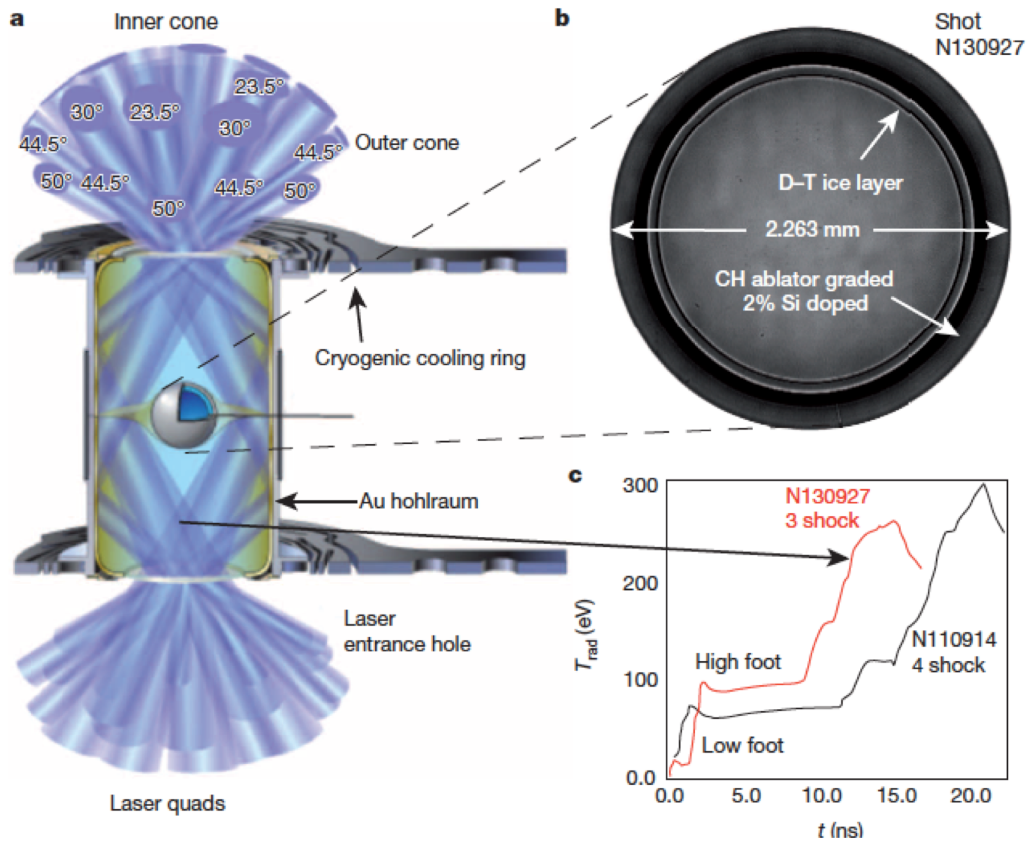
T-2 Seminar, July 7th 2020

Abstract

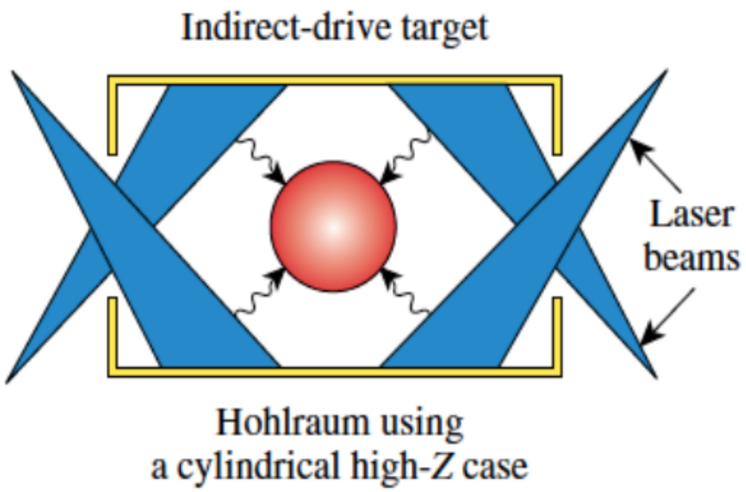
Physically realized electron gas systems usually reside in either the quantum non-degenerate or fully degenerate limit, where the average de Broglie wavelength of the thermal electrons becomes comparable with the interparticle distance between electrons. A few systems, such as young brown dwarfs and the cold dense fuels created in imploded cryogenic capsules at the National Ignition Facility, lie between these two limits and are partially degenerate. The National Ignition Facility has the unique capability of varying the electron quantum degeneracy by adjusting the laser drive used to implode the capsules. This allows experimental studies of the effects of the degeneracy level on plasma transport properties. By measuring rare nuclear reactions in these cold dense fuels, we show that the electron stopping power, which is the rate of energy loss per unit distance travelled by a charged particle, changes with increasing electron density. We observe a quantum-induced shift in the peak of the stopping power using diagnostics that measure above and below this peak. The observed changes in the stopping power are shown to be unique to the transition region between non-degenerate and degenerate plasmas. Our results support the screening models applied to partially degenerate astrophysical systems such as young brown dwarfs.

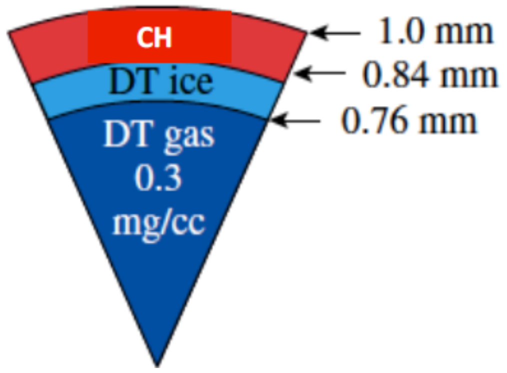
The National Ignition Facility aims to achieve Fusion Ignition through indirect drive of inertial confinement capsules



- A capsule of DT gas, surrounded by a layer of DT ice and a CH ablator, is placed inside a Au hohlraum
- 192 laser beams create an x-ray bath inside the hohlraum
- The laser pulse shape depends on the design, with highest yields coming from 'High Foot' pulses
- The x-rays ablate off the outer layer of the capsule
- The capsule implodes and the central DT gas burns

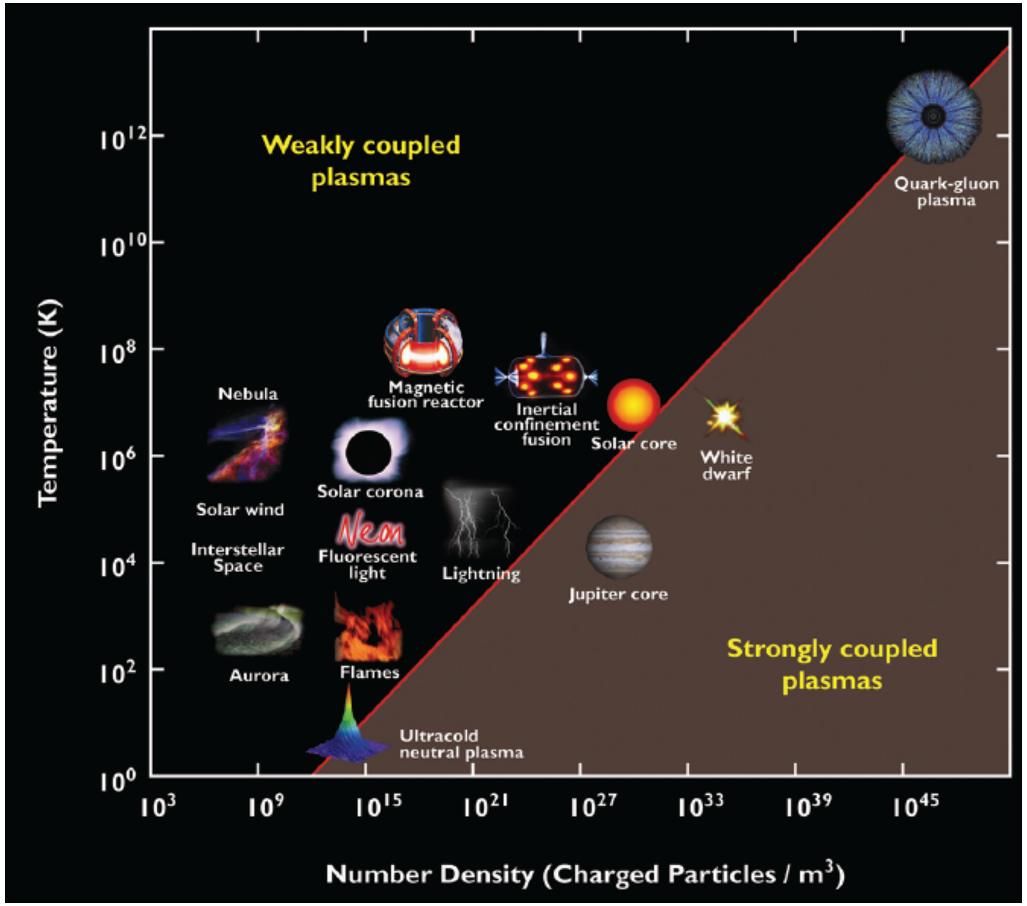
The Capsule Involves Three Layers: DT Gas, DT Ice, and a Plastic Ablator





- The burn takes place in the inner DT gas layer.
- If ignition were achieved, the burn would propagate into the DT ice, and the yield would increase 100 fold.
- But to-date the DT ice layer remains cold (~0.2 keV).
- The cold DT fuel is also quite dense (~5x10^{25} cm^{-3}).
- This results in a quantum degenerate DT ice layer that allows studies of unique plasmas conditions.

Nuclear and Plasma Physics studies span a huge range of densities and temperatures



In all cases the plasma is characterized by the coupling:

$$\Gamma = \frac{Potential\ Energy\ (Coulomb)}{Kinetic\ energy\ (temperature)} = \frac{Z\,e^2}{\langle r\rangle\theta}$$

Γ< 1 the plasma is weakly coupled
- hot, low density, e.g., magnetic fusion

Γ > 1 the plasma is strongly coupled - cool, high density, e.g., white dwarfs

Γ ~1 transition region from non-degenerate to degenerate – NIF cold fuel conditions

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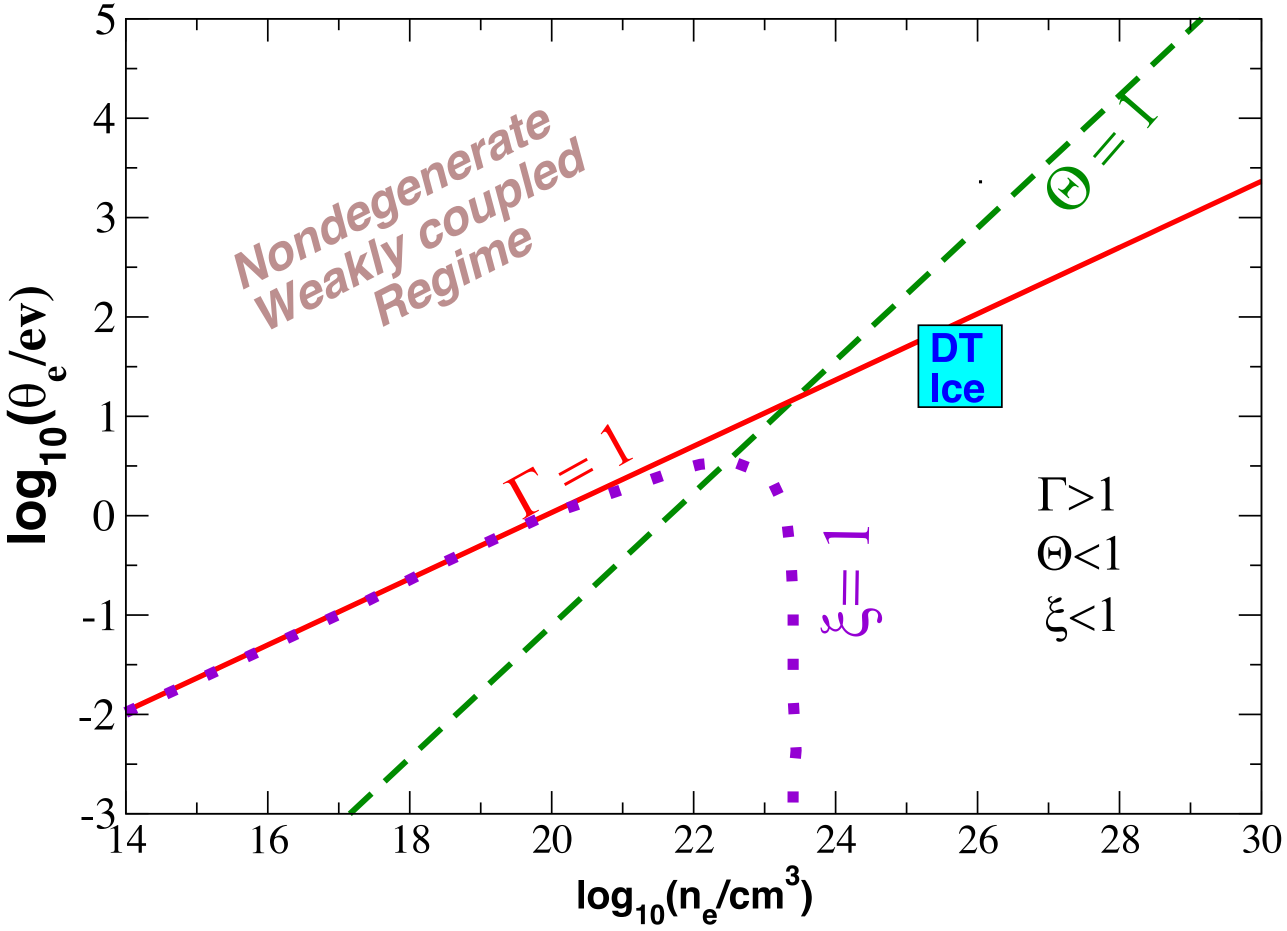
If the temperature is lower than the Fermi temperature, the plasma is degenerate and new quantum effects come into play



$$\theta_{Fermi} = \frac{\hbar^2}{2m}(3\pi^2\rho)^{2/3}$$

Degeneracy of the plasma

$$\Theta = \frac{\theta}{\theta_{Fermi}}$$

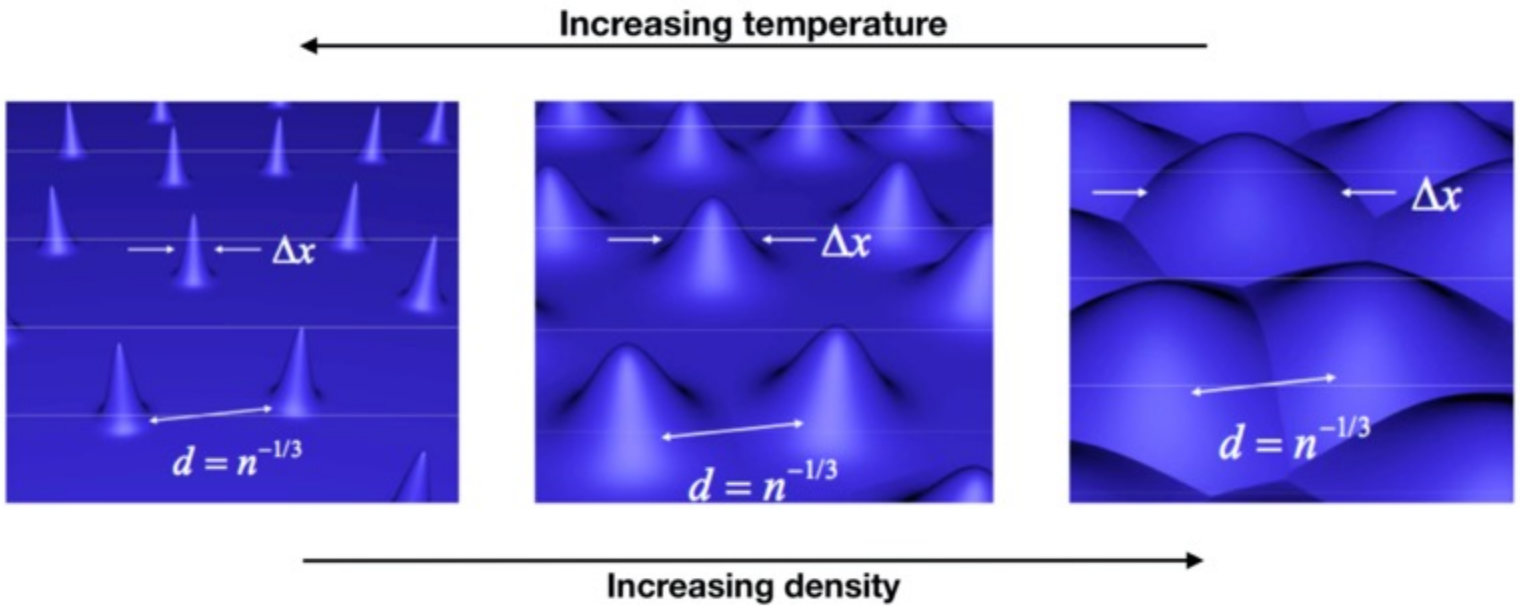
if $\Theta > 1$:

Pauli blocking affects the electron collisionality

Plasma properties determined by

quantum coupling: $\xi = \dfrac{Z\,e^2}{\langle r\rangle\,\theta_{effective}}$

The Phenomenon of Quantum Degeneracy affects the properties very cold and/or very dense matter

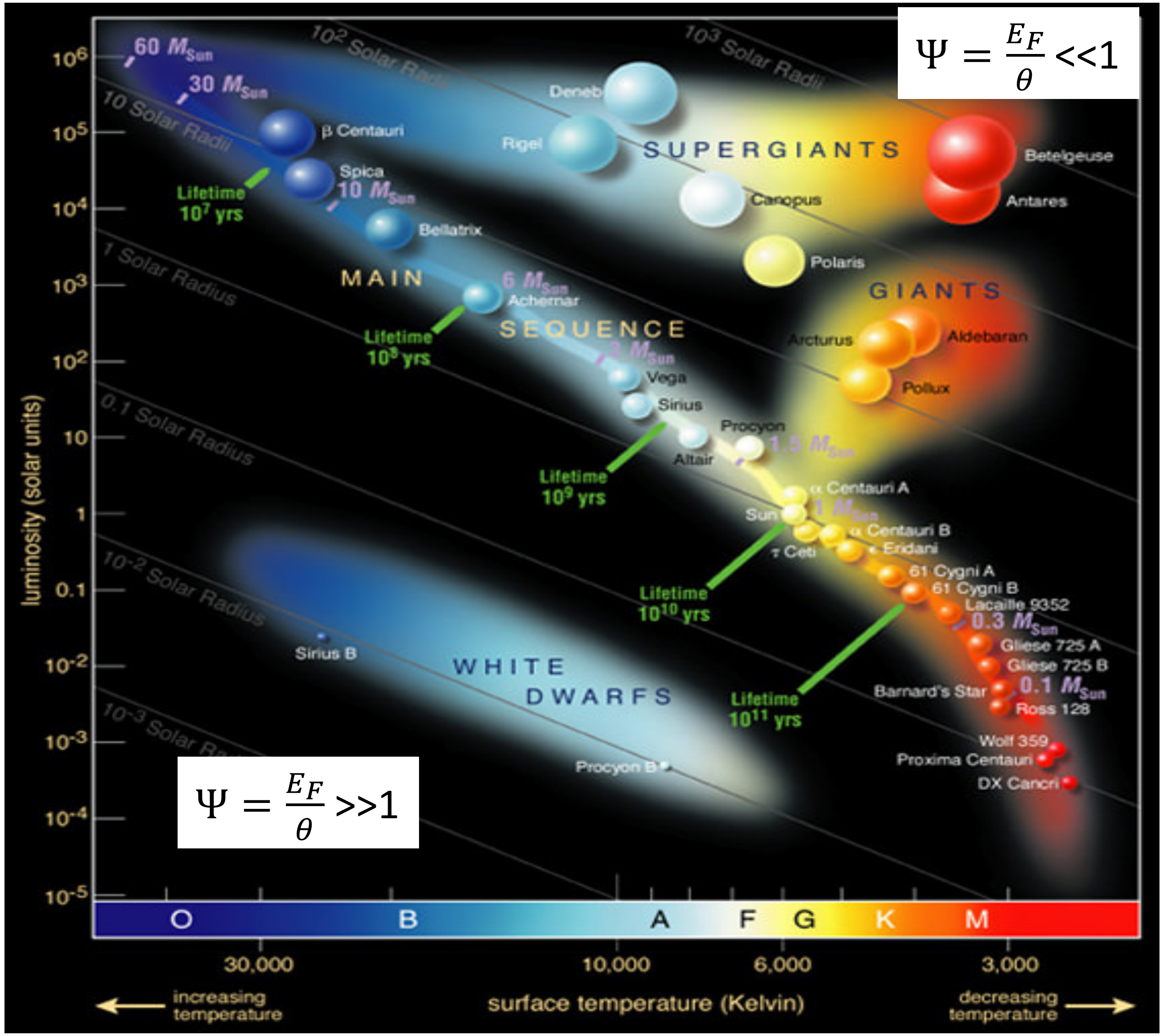


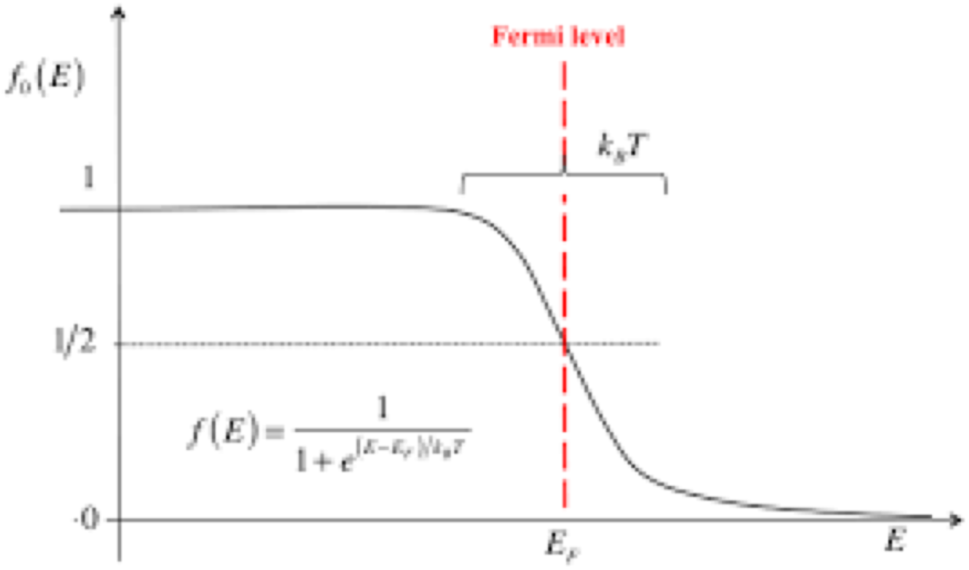
A plasma becomes degenerate when the deBroglie wavelength ($\lambda = h/p$) of the electrons becomes comparable to the inter-particle distance ($d = n^{-1/3}$) between electrons.

The degree of degeneracy of a system is the ratio of the Fermi Energy to the temperature

$$\Psi = \frac{E_F}{\theta}; \quad E_F = \frac{\hbar^2}{m_e}\left(3\pi^2\rho_e\right)^{3/2}$$

Most system are either fully non-degenerate (e.g., main sequence stars) or fully degenerate (e.g., white dwarfs, neutron stars and electrons in metals)

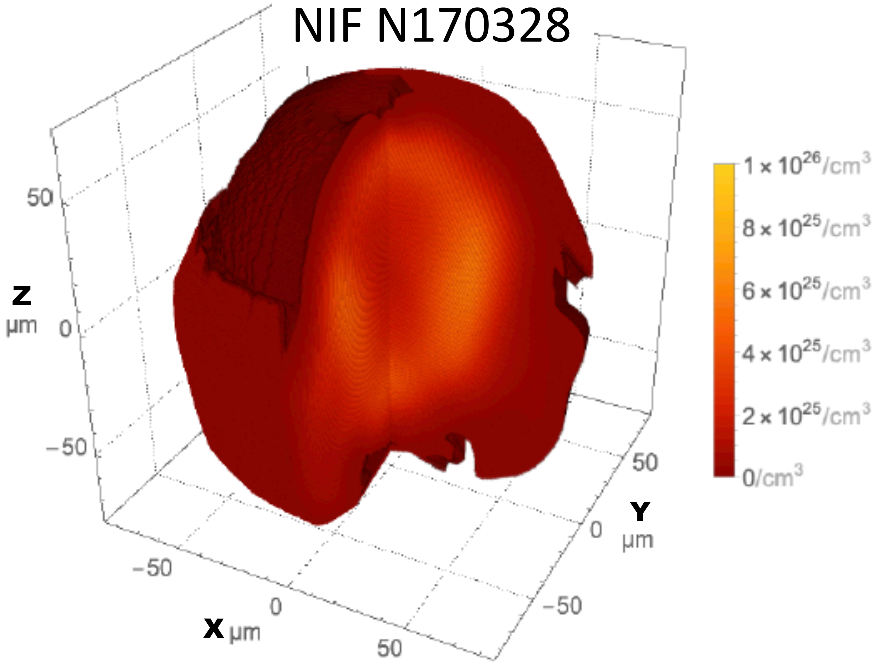


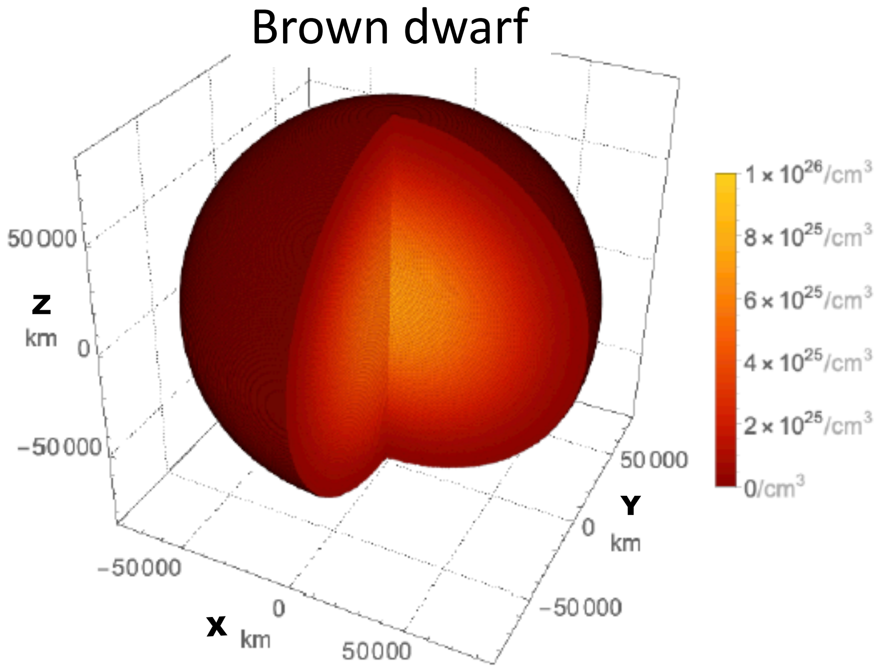


Fully quantum degenerate electron configurations are well-studied in solid state physics and astrophysics.

Degeneracy changes plasma properties, including viscosity, electron screening, e-ion equilibration times, thermal and electrical conductivity, stopping powers, etc.

The transition region between non-degenerate and degenerate quantum limits is poorly studied and experimentally challenging

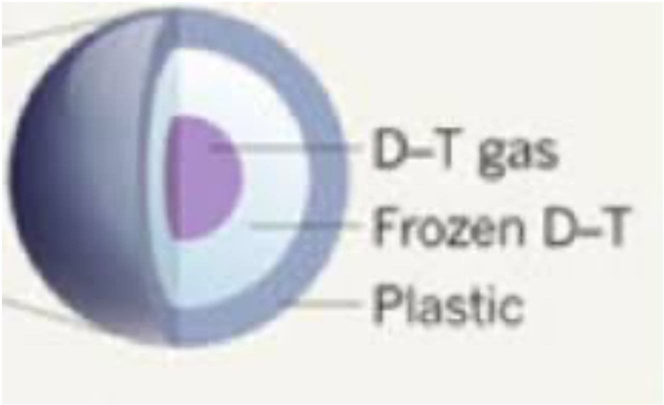


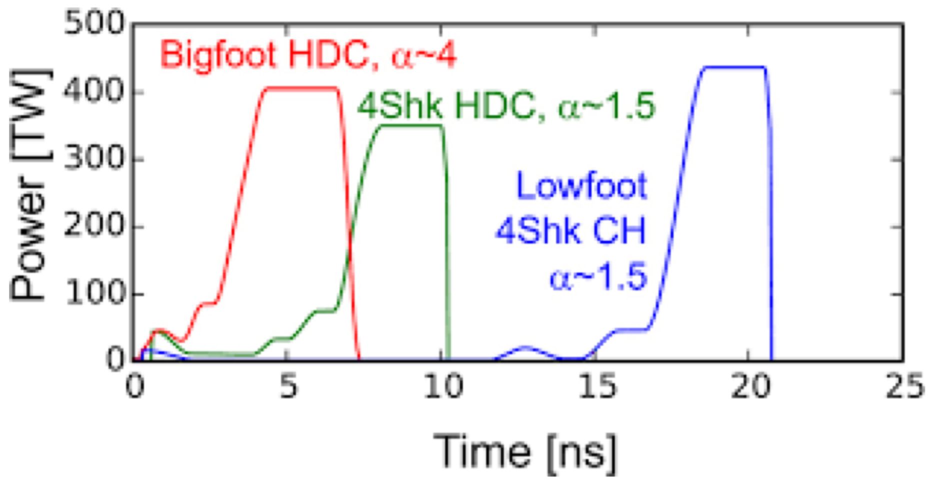


Two systems known to be partially degenerate and very similar to one another are NIF cold fuels and astrophysical brown dwarfs.

They both exhibit a temperature (θ~ 0.2 keV) and a degree of degeneracy $\Psi = \frac{E_F}{\theta}$ **~ 1- 4**

NIF aims to get the cold fuel of cryogenic ignition capsules as degenerate as possible





- The DT ice starts frozen
- The implosion results in a compressed cold fuel that is determined by the implosion adiabat, (i.e., by the ratio of the pressure at peak implosion velocity to the Fermi pressure).
- As the laser drive varies, the implosion dynamics change, and the degree of quantum degeneracy of the final cold fuel varies.
- The RIF program searches for evidence of these changes, through the sensitivity of RIFs to changes in the plasma transport properties.

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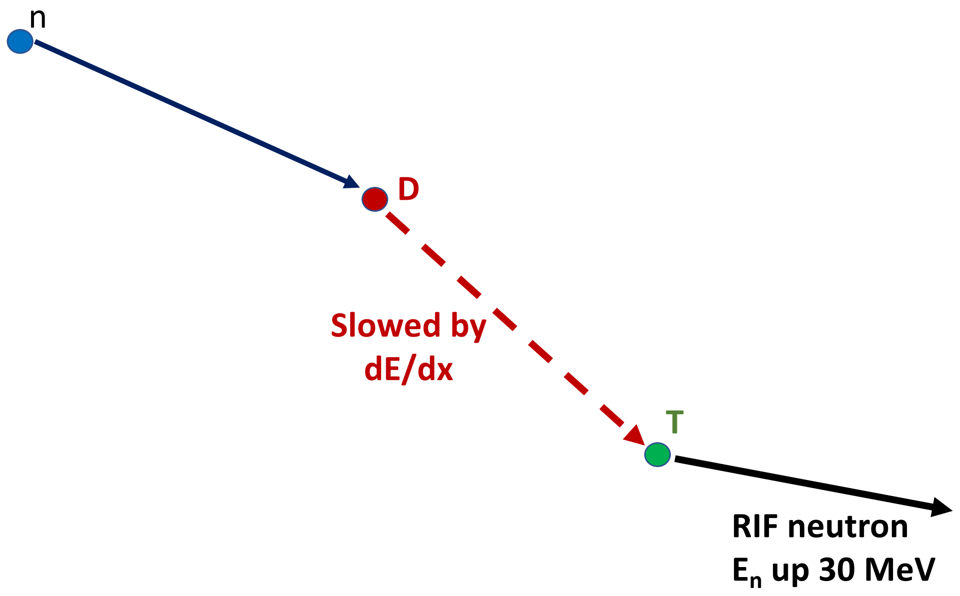
The cold fuel is not burning, but rare reactions-in-flight (RIFs) are taking place. We use these to probe the quantum state of the cold fuel.

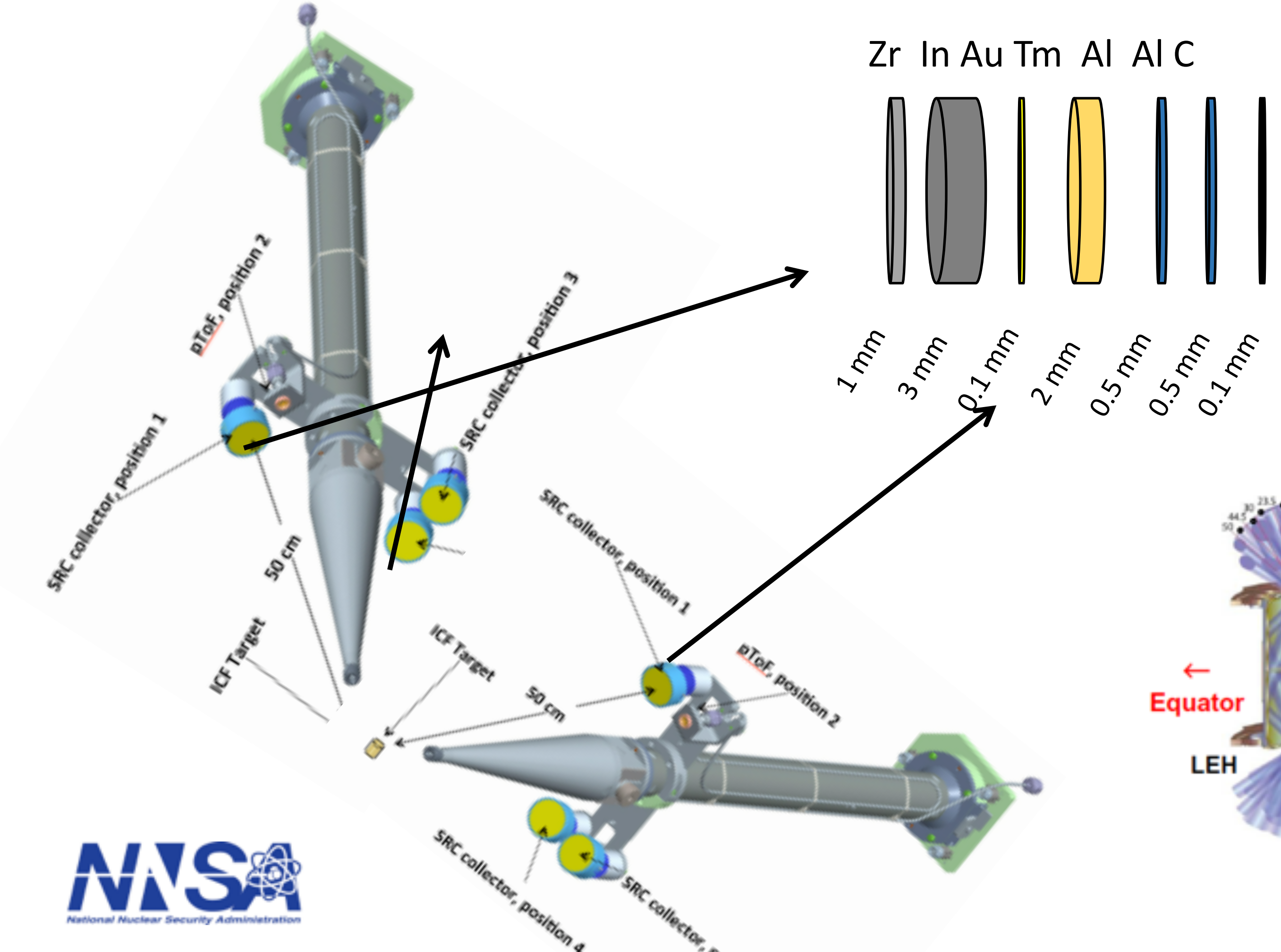


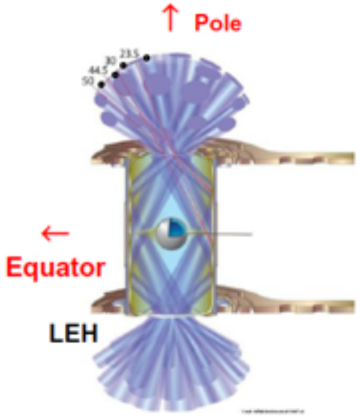
- A 14 MeV neutron, born in the hotspot, elastically scatters a cold fuel D or T ion up to MeV energies.
- The knock-on (KO) ion undergoes a DT reaction before loosing all of its kinetic energy, producing a RIF neutron.
- The shape and magnitude of the RIF spectrum are determined by the stopping power (dE/dx) in the dense cold degenerate fuel.
- We search for degeneracy-induced effects in the shape and magnitude of the RIF spectrum, and relate these to changes in the stopping power.

Measuring RIFs at NIF is very Challenging: RIF/total neutrons ~ 10^{-4}- 10^{-5} . Eliminating backgrounds requires very special activation techniques

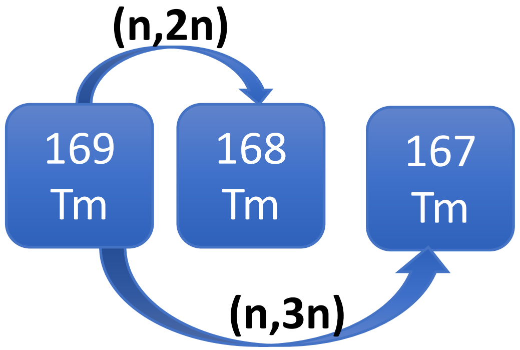
First RIFs were measured in 2013 by neutron activation

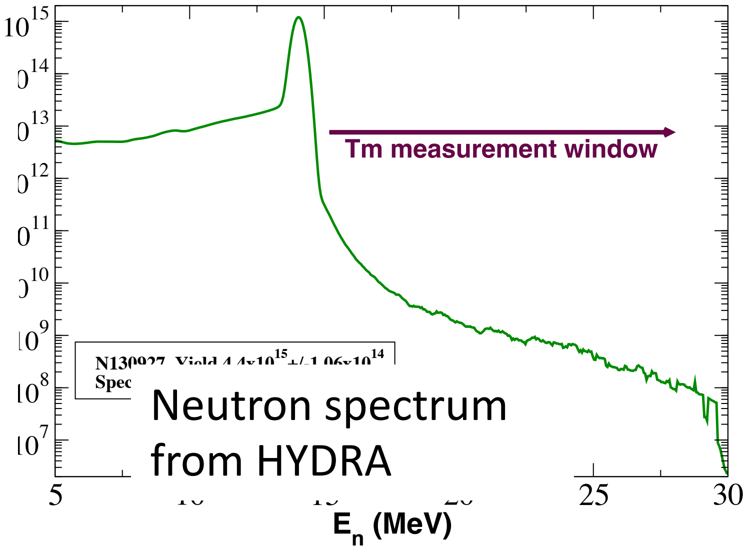
- Use a 2 mm (or 0.5 mm) Tm foil
- 50 cm from TCC, with 1 on the equator and 1 on the pole.



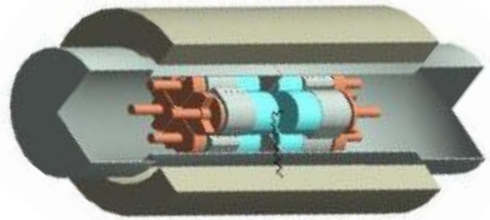


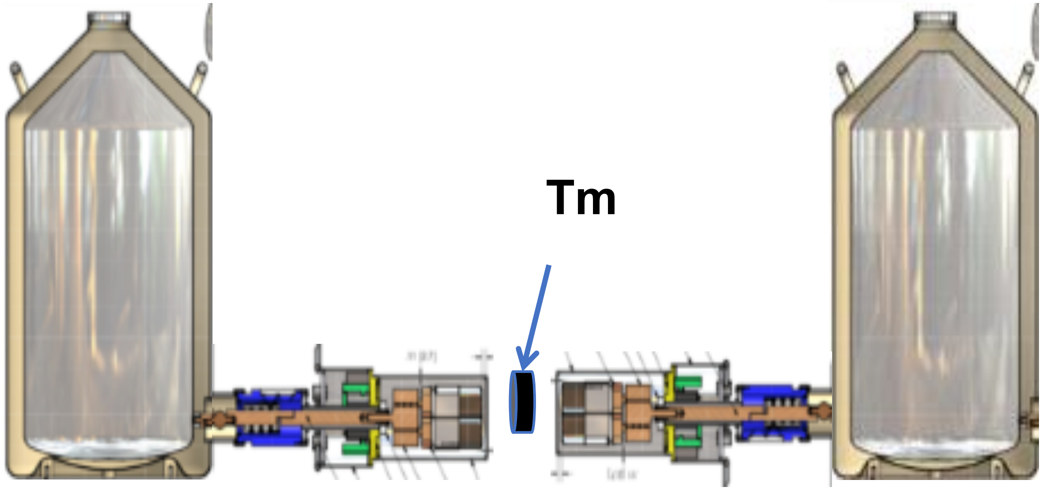
$^{169}Tm(n,3n)^{167}Tm$ E_{Th}=15 MeV



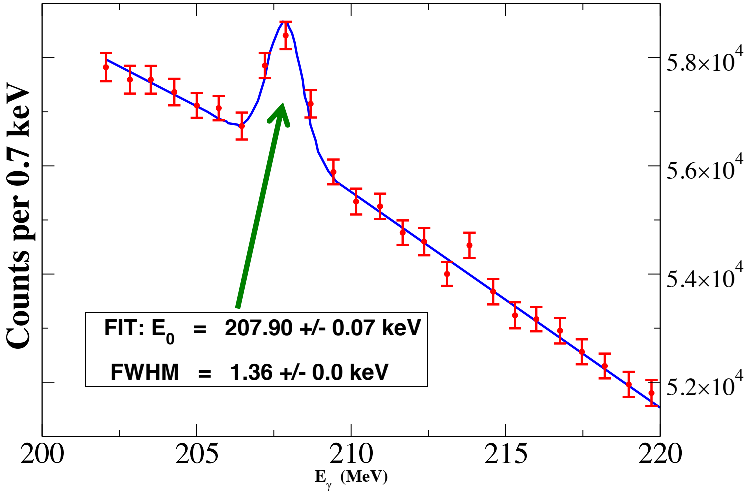


RIF measurements are feasible using of a segmented clover detector, which discriminates against the huge background in the foil induced by the 14 MeV neutrons

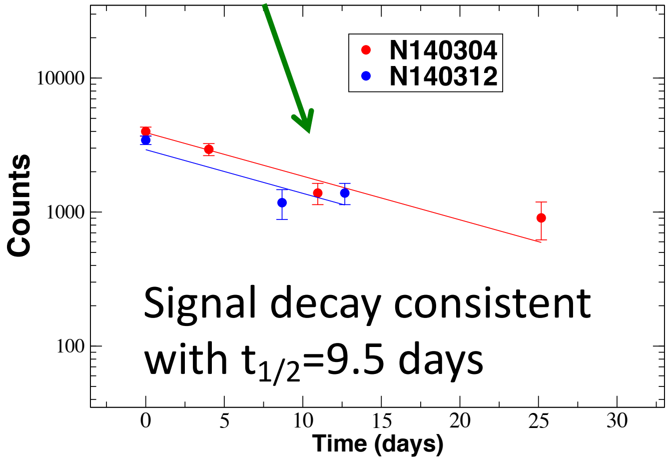




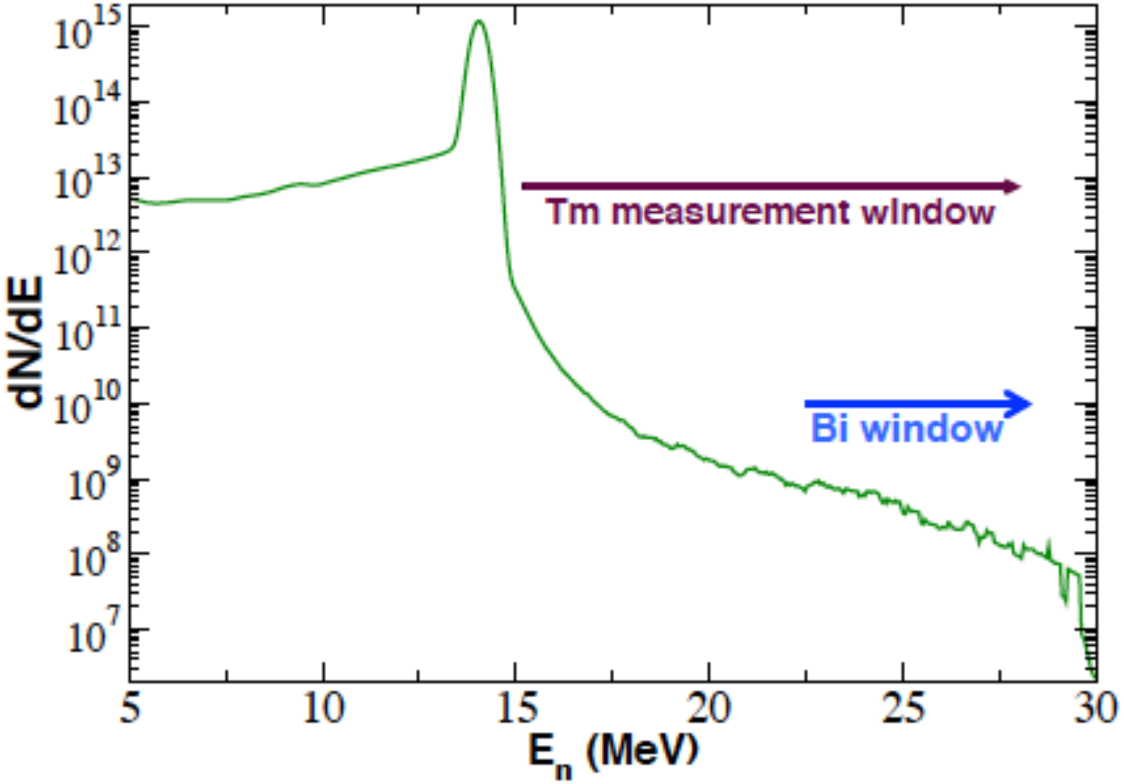
Two highly efficiency clover HPGe detectors
Each clover consists of 4 Ge crystals
Active 4π NaI(Tl) Compton Suppressor



RIF signals is a 208 keV gamma-ray from the decay of ^{167}Tm, with a 9.5 day half-life



A Second Clover Detector was recently installed at Livermore to measure the shape of the RIF spectrum via the $^{209}Bi(n,4n)^{206}Bi$ Reaction

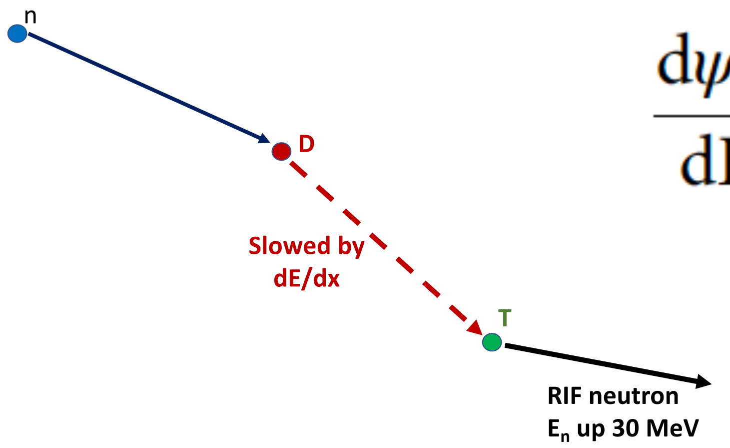


The Tm foils are shipped back to LANL for counting and the Bi foils counted at LLNL

Tm: E_n ~<20 MeV>
Bi : E_n ~ <25 MeV>

How does quantum degeneracy affect the RIFs?

$$\frac{1}{\mathrm{d}V}\frac{\mathrm{d}N_{\mathrm{RIF}}}{\mathrm{d}E_{\mathrm{RIF}}} = n_{\mathrm{d}}\int \frac{\mathrm{d}\psi^{\mathrm{t}}_{\mathrm{ko}}}{\mathrm{d}E_{\mathrm{ko}}}\sigma_{\mathrm{dt}}\frac{\mathrm{d}F}{\mathrm{d}E_{\mathrm{RIF}}}\mathrm{d}E_{\mathrm{ko}} + n_{\mathrm{t}}\int \frac{\mathrm{d}\psi^{\mathrm{d}}_{\mathrm{ko}}}{\mathrm{d}E_{\mathrm{ko}}}\sigma_{\mathrm{dt}}\frac{\mathrm{d}F}{\mathrm{d}E_{\mathrm{RIF}}}\mathrm{d}E_{\mathrm{ko}}$$

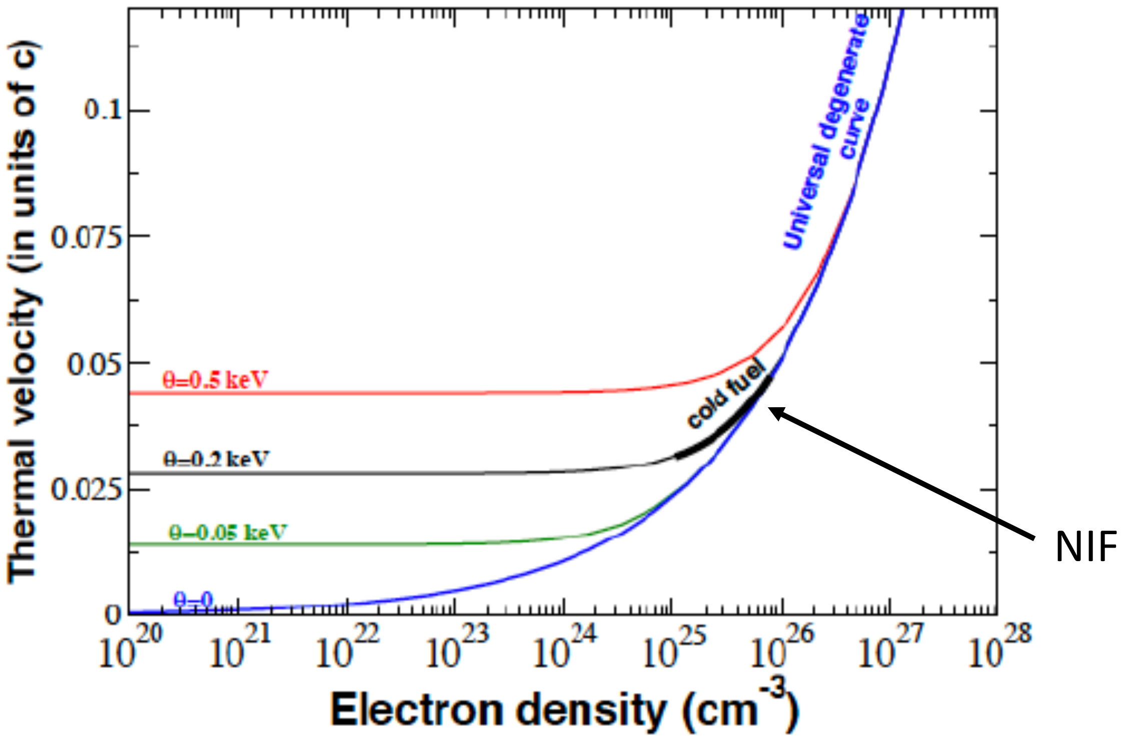


$$\frac{\mathrm{d}\psi^{\mathrm{d(t)}}_{\mathrm{ko}}}{\mathrm{dE}_{\mathrm{ko}}} = \frac{\Phi_n n_{\mathrm{d(t)}}\sigma_{\mathrm{ko}}}{|\mathrm{d}E/\mathrm{d}x(E_{\mathrm{ko}})|}\int_{E_{\mathrm{ko}}}^{\infty}\mathrm{d}E_0\, q(E_0),$$

KO ion spectrum is inversely proportional to the stopping

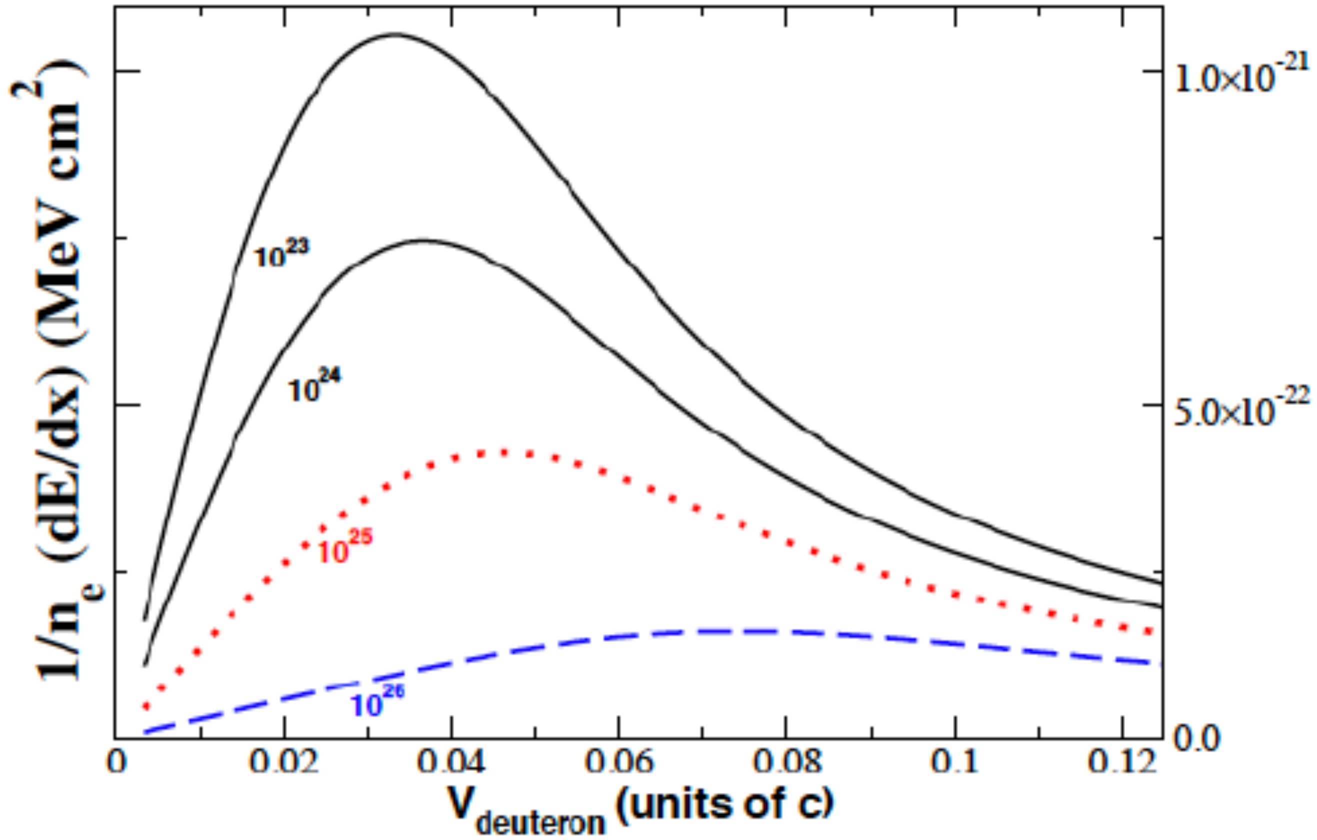
Any degeneracy-induced changed in dE/dX
$\Rightarrow$a change in the shape of the KO ion spectrum
$\Rightarrow$ a change in the shape of the RIFs

The main effect of quantum degeneracy on stopping powers is the change in plasma the average electron velocity



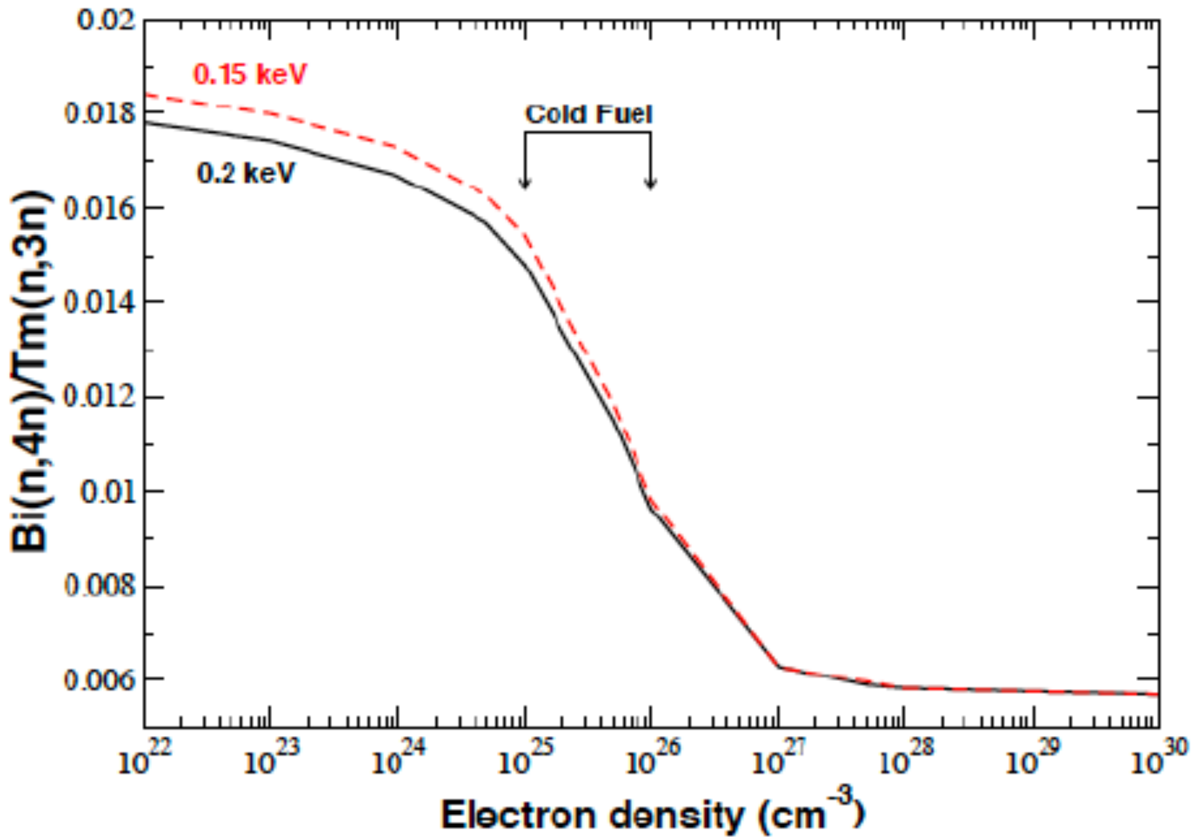
- ❖ For low density and non-degenerate plasmas, the thermal velocity is only a function of temperature
- ❖ For very high densities, the plasma becomes degenerate and the thermal velocity is only a function of density
- ❖ For intermediate densities, the thermal velocity is a function of <u>both</u> density and temperature

The stopping power peaks when the ion velocity is equal to the average electron velocity. Degeneracy pushes this peak to higher and higher velocity.



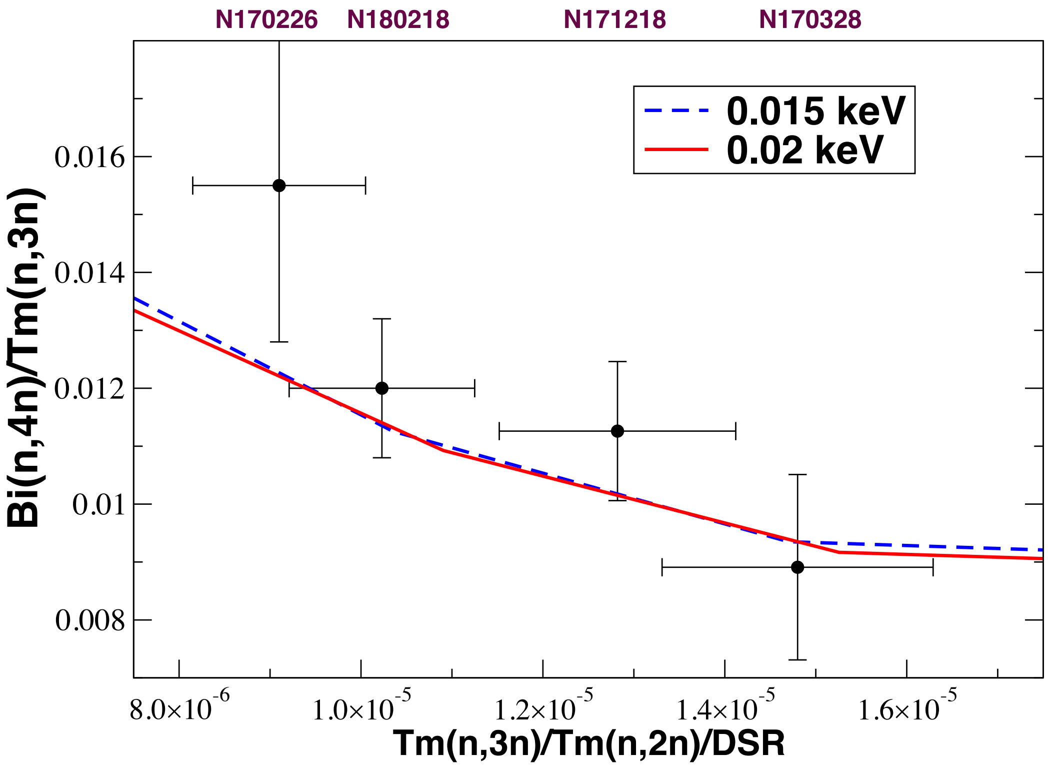
To search for this shift in the Bragg peak we measure above and below the peak

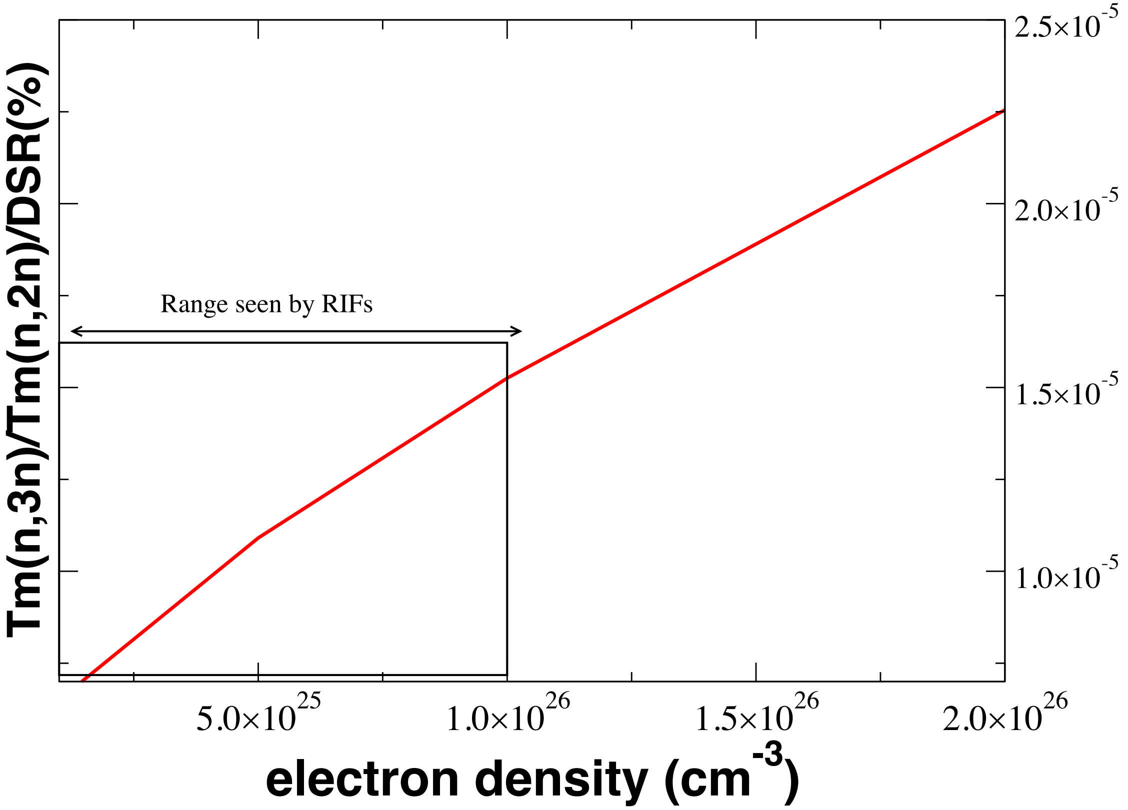
The predicted degeneracy induced decrease in the Bi/Tm RIF ratio by about a factor of two



The effect results from the shift in Bragg peak to higher energies

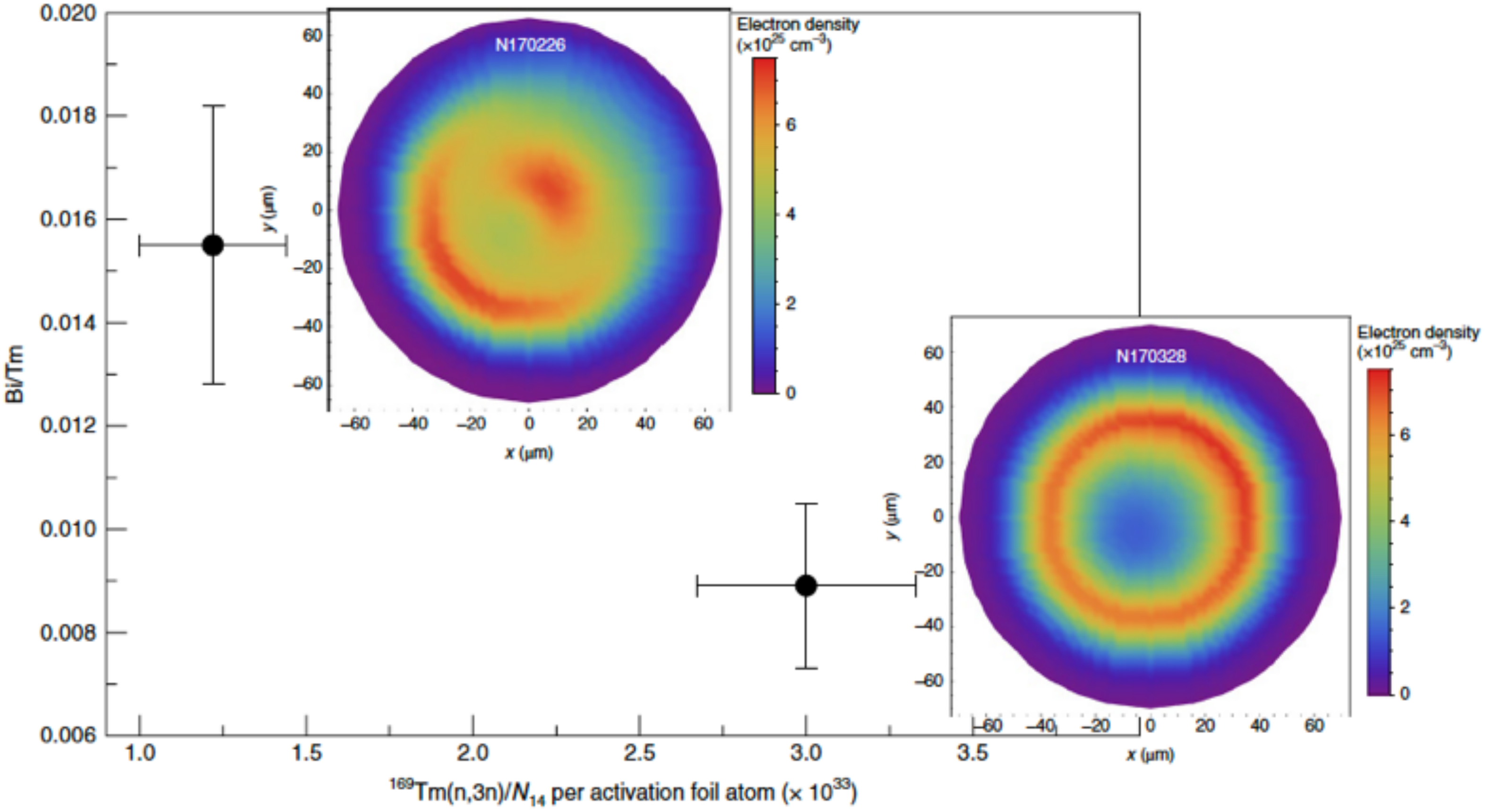
The Bi/Tm ratio (~<25 MeV>/<20 MeV>) measures the harness of the RIF spectrum and decreases by a factor of two with increasing electron density.





The decrease supports a shift in the Bragg peak at the 90% confidence level.
For a non-degenerate plasma the Bi/Tm ratio would always remain above 0.016
The data rule out a purely non-degenerate or purely degenerate plasma with 3σ confidence.

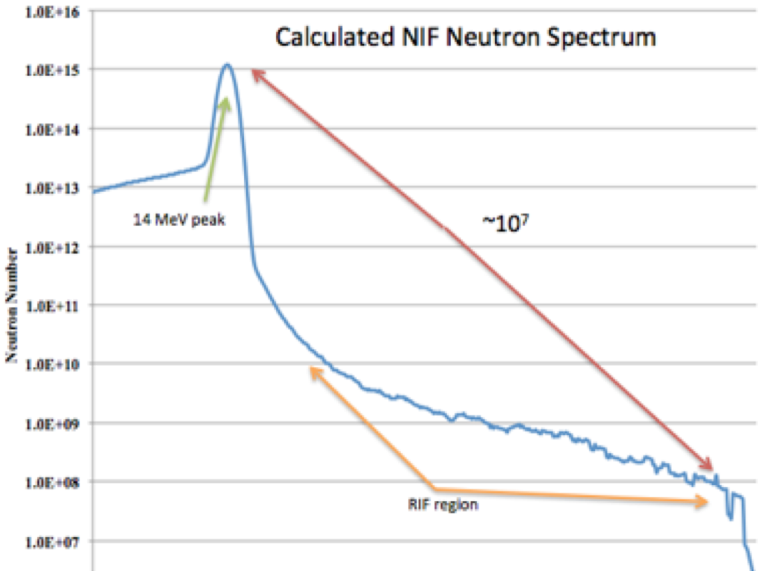
Find a correlation between RIF ratios and the neutron images for the shots



The more dense cold fuel of N170328 produced more RIF per 14 MeV neutron yield but a softer RIF spectrum than the less dense cold fuel of shot N170226

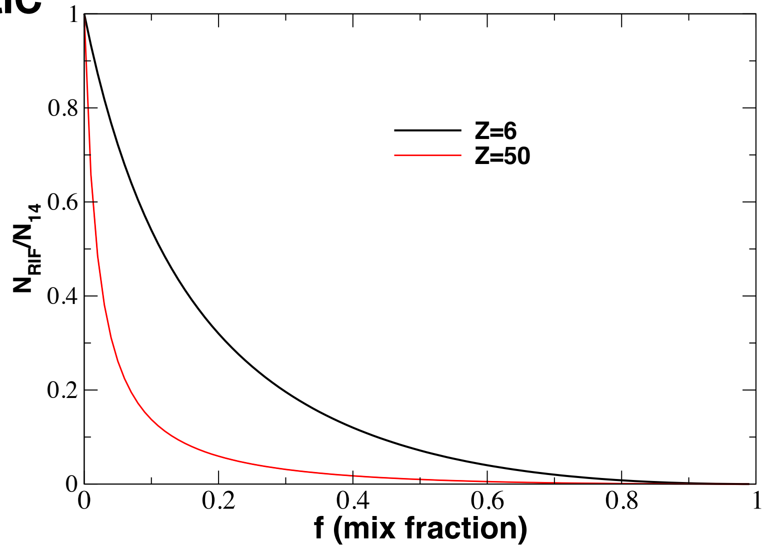
Future Directions

- Developing an nTOF capability for RIFs.
  Can currently measure RIF by nTOF to 17 MeV at NIF
  Working to go out to ~30 MeV, which involves 7 orders of magnitude
  Will allow us to distinguish more sensitive changes in RIF spectra



- RIF signal for Double Shell designs provides a sensitive mix diagnostic
  - RIF signal is suppressed by mix
  - This effect is maximal of Double Shell designs, with high-Z shell
  - Planning combined analysis with DS Radchem data

$$\frac{(N_{RIF}/N_{primary})_{MIX}}{(N_{RIF}/N_{primary})_{CLEAN}} = \frac{(1-f)^2}{1-f+Z_{\mathrm{eff}}\, f}\left(\frac{\theta_e^{mix}}{\theta_e^{DT}}\right)^{3/2}$$



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